Non-Leaky Coplanar (NLC) Waveguides with Conductor Backing

Yaozhong Liu, *Student Member, IEEE,* Kimin Cha, *Student Member, IEEE,* and Tatsuo Itoh, *Fellow, IEEE*

***Abstract*—In this paper, we present a structure called a non-leaky coplanar (NLC) waveguide with conductor backing. It is a multilayered structure with two possible configurations. The spectral domain approach with a complex root searching procedure is used to investigate leakage phenomena. The simulation results confirm that the leakage in conductor-backed coplanar waveguide (CBCPW) occurs in the form of wave in the parallel plate waveguide with infinite width. The results show that the leakage in the multilayered structure can be removed if the geometrical and material parameters of the structure are chosen appropriately. Experiments were carried out to investigate the transmission of these structures. It was found that the resonance in the transmission of finite-width conductor-backed coplanar waveguide (FW-CBCPW) is caused by the energy leakage from the dominant CPW mode. The resonance is eliminated in the NLC waveguides. These NLC waveguides are feasible and practical in the uniplanar MMIC design due to their planar nature.**

I. Introduction

The UNIPLANAR technology makes use of the coplanar waveguide (CPW) and slotline (SL) extensively and provides an alternative to the MMIC based on the microstrip line. The conductor-backed coplanar waveguide (CBCPW) [1] and slotline (CBSL) are preferred in the MMIC due to several advantages, such as improved mechanical strength and heat sinking ability. However, the presence of conductor backing causes certain serious problems such as the power leakage into transverse direction, resulting in unexpected or even harmful coupling to the neighboring transmission lines or devices [2], [3]. Such leakage phenomena have drawn significant interest because of their importance in both basic understanding of guided wave phenomena and practical applications. Several theoretical methods have been proposed to investigate the leaky wave propagation, such as mode-matching method [2], [4], Wiener-Hopf/generalized scattering matrix technique (WH/GSMT) [5], and spectral domain approach [6], [7].

In practice, the side conductor plane and substrate of coplanar waveguide are always finitely wide, thus we generally have finite-width conductor-backed coplanar waveguide (FW-CBCPW). In a FW-CBCPW, the energy leaks away from the dominant CPW mode in the form of parallel plate waves. These parallel plate waves will bounce back and forth inside the circuit due to the circuit truncation, causing the resonance in the transmission. This phenomenon has been observed and analyzed theoretically and experimentally [8], [9]. Such a phenomenon severely deteriorates the CBCPW circuit performance and makes CBCPW unusable in the microwave and millimeter wave circuit design.

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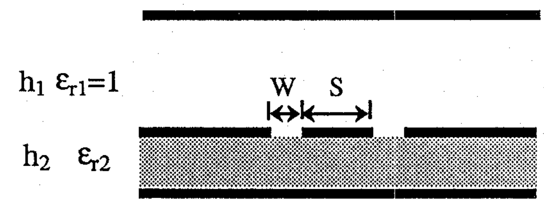

Fig. 1. Cross-section of the covered conductor-backed coplanar waveguide (CBCPW).

In this paper, we propose a non-leaky coplanar (NLC) waveguide with conductor backing. There are two possible configurations [10]. The first one is the structure of CBCPW with an additional top layer whose dielectric constant is higher than that of the substrate; the second is the one with additional bottom layer whose dielectric constant is lower. These structures are analyzed by the spectral domain approach with a complex root searching procedure similar to the one described in [6], [7]. The obtained results for the phase and attenuation constants show that the structures have a sharp transition from leaky to non-leaky when the thickness of the additional layer is increased, indicating that these structures are no longer leaky and can be used to prevent the leakage. The results further confirm the leakage is due to presence of parallel plate wave which is slower than the dominant mode of coplanar waveguide.

The experiments were carried out to confirm the theoretical prediction. First, the transmission of a FW-CBCPW was measured and strong resonance was observed as reported in [8]. Two finite-width non-leaky coplanar (FW-NLC) waveguides were fabricated and their transmissions were then measured. The results show that the resonance is eliminated in these two NLC waveguides and the transmission is improved.

II. Theory

Fig. 1 shows the cross-sectional geometry of a conductor-backed coplanar waveguide (CBCPW). The top metal cover is introduced for mathematical convenience and is placed far enough without effect on mode propagation. We assume the conductivity of the conductor forming the waveguide is infinite and the loss tangent of dielectric is zero, so there is no ohmic and dielectric loss.

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This structure always leaks energy into transverse direction. As stated in [11], the qualitative reasoning is as follows. The outer lateral conductor of coplanar waveguide and the back conductor form a parallel plate waveguide. The effective dielectric constant (EDC) of the relevant dominant parallel plate mode (supported by the parallel plate waveguide with the same dielectric layer and infinitely wide top and bottom conductor plates) is ε_{r2}, while the EDC of the dominant CPW mode of conductor-backed CPW is between ε_{r1} and ε_{r2} ($\varepsilon_{r1} = 1$ and $\varepsilon_{r2} > \varepsilon_{r1}$) and less than ε_{r2}. Thus, the dominant CPW mode is always faster than the dominant parallel plate wave. As a consequence, the dominant CPW mode is unconditionally leaky over all frequency range. At a low frequency, only the dominant parallel plate wave (TEM type) makes contribution to the energy leakage. However, the higher-order parallel plate waves may propagate with a slower phase velocity than that of the dominant CPW mode when the working frequency is sufficiently high. Under this situation, the higher-order parallel plate waves will join the dominant parallel plate wave to make the contribution to energy leakage.

A modified spectral domain approach (SDA) has been employed to analyze the leaky wave propagation [6], [7]. The formulation procedure is same as the one in conventional SDA [12]. Fourier transforms of the tangential electrical fields ($\tilde{E}_x$ and $\tilde{E}_z$) and current densities ($\tilde{J}_x$ and $\tilde{J}_z$) are related via the following equation:

$$\begin{bmatrix} \tilde{J}_x(k_x) \\ \tilde{J}_z(k_x) \end{bmatrix} = \begin{bmatrix} \tilde{Y}_{xx}(k_x,\, k_z) & \tilde{Y}_{xz}(k_x,\, k_z) \\ \tilde{Y}_{zx}(k_x,\, k_z) & \tilde{Y}_{zz}(k_x,\, k_z) \end{bmatrix} \begin{bmatrix} \tilde{E}_x(k_x) \\ \tilde{E}_z(k_x) \end{bmatrix} \quad (1)$$

where $\tilde{Y}_{xx}$, $\tilde{Y}_{xz}$, $\tilde{Y}_{zx}$, and $\tilde{Y}_{zz}$ are the spectral domain Green's functions and can be formulated with the immitance approach [13]. The propagation constant k_z is complex. Its real part gives the phase constant while its imaginary part represents the attenuation constant, i.e., $k_z = \beta - j\alpha$.

The aperture fields E_x and E_z are expanded in terms of Chebyshev-Maxwellian basis functions [7] and Galerkin's method in the spectral domain is then applied to (1). However, the contour of integration in the complex k_x plane is deformed from the real axis as shown in Fig. 2 to include the residue contribution associated with the wave propagation of parallel plate wave or the surface wave [6], [7]. A complex root searching is then used to solve the complex propagation constant.

A computer program is written based upon the above approach and the computed results were checked against the published data in [5], [7]. The program is then applied to structure in Fig. 1 with the results shown in Fig. 3. It is clear that the structure is leaky over all the frequency range.

As mentioned in Section I, two multilayered structures have been proposed to control the leakage. The idea is to make the effective dielectric constant of the dominant CPW mode higher than that of the relevant dominant parallel plate mode by introducing an additional dielectric layer. The first structure is the one with an additional top layer whose dielectric constant is higher than that of substrate, while the second one is with an additional bottom layer whose dielectric constant is lower. They are shown in Fig. 4(a) and (b), respectively, where ε_{r2} is greater than ε_{r3}. The second structure can

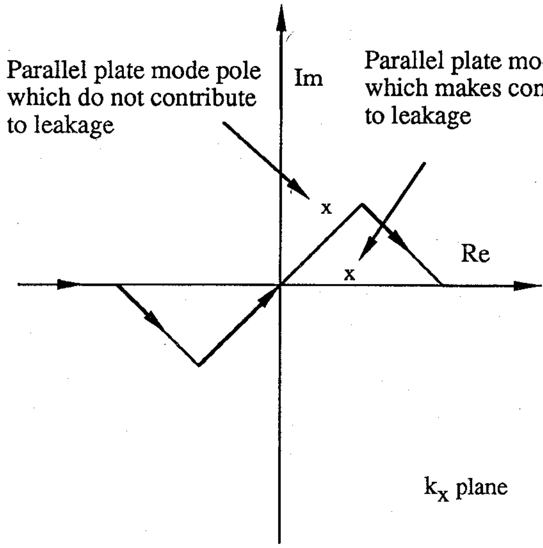

Fig. 2. Integration contour in the complex k_x plane.

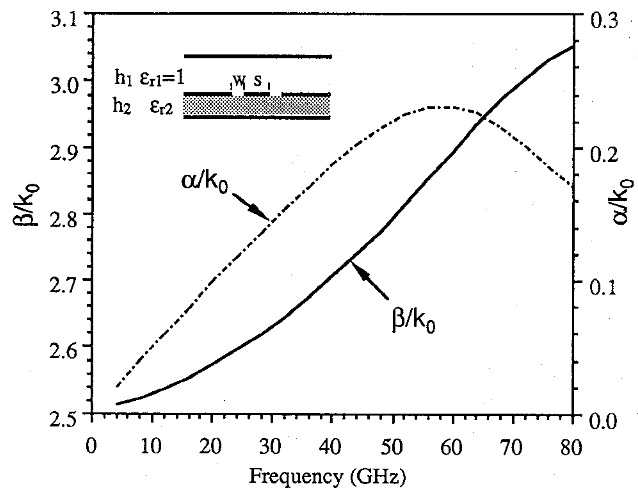

Fig. 3. Normalized phase and attenuation constants versus frequency for CBCPW. $\varepsilon_{r2} = 10.5$, $h_1 = 20.0$ mm, $h_2 = 0.635$ mm, $W = 0.454$ mm, $S = 0.42$ mm.

also be viewed as the one with a dielectric layer of higher dielectric constant, which is placed between the metal and the substrate. It should be noticed that both conventional single-layered CPW and CBCPW can be viewed as extreme cases of either multilayered structures. For instance, letting h_2 equal zero in Fig. 4(a) will result in the conventional single-layered CBCPW. The structure Fig. 4(a) will become a conventional single layered CPW if we let ε_{r3} and h_3 equal to unity and infinity respectively.

It is obvious that the effective dielectric constant of the dominant CPW mode of structure shown in Fig. 4(a) will be increased by introducing such an additional dielectric layer of higher dielectric constant. Because the effective dielectric constant of the relevant dominant parallel plate mode is still kept as ε_{r3}, the effective dielectric constant of the dominant CPW mode may become larger than that of relevant dominant parallel plate mode if the increment in effective dielectric constant of the dominant CPW mode is sufficiently large. In

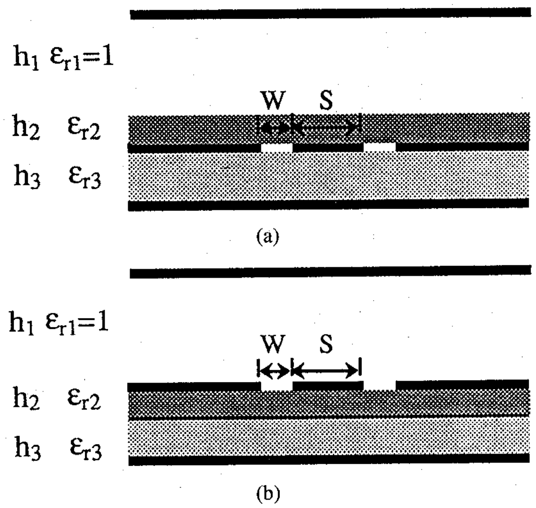

Fig. 4. Cross-sections of two multilayered conductor-backed CPW's.

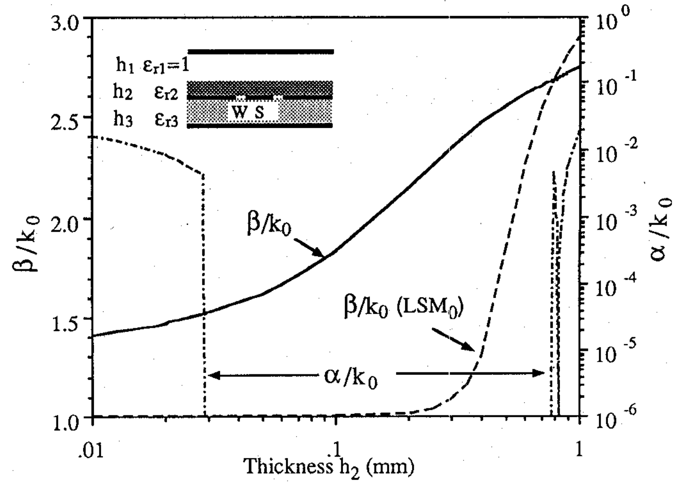

Fig. 5. Normalized phase and attenuationconstants vs. h_2. $\varepsilon_{r2} = 10.5$, $\varepsilon_{r3} = 2.33$, $W = 0.454$ mm, $S = 0.420$ mm, $h_1 = 20.0$ mm, $h_3 = 0.635$ mm, $f = 50$ GHz.

contrast, the additional layer of lower dielectric constant in the structure shown in Fig. 4(b) decreases the effective dielectric constants of both dominant CPW and relevant parallel plate modes. However, the decrease of effective dielectric constant of the dominant CPW mode is smaller because the field of the dominant CPW mode is mainly confined in the slot region. Thus it is still possible to have the effective dielectric constant of the dominant CPW mode larger than that of the relevant parallel plate mode. The difference between the effective dielectric constants of the dominant CPW and relevant parallel plate mode is determined by the geometrical and material parameters of the structure and the working frequency. For a properly designed waveguide of multilayered structure, the effective dielectric constant of the dominant CPW mode will be higher than that of relevant parallel plate mode over certain frequency range. Therefore, the dominant CPW mode is slower than the parallel plate wave and becomes purely bound over certain frequency range, indicating the possibility of non-leaky coplanar (NLC) waveguide with conductor backing.

Let us first look at the multilayered structure shown in Fig. 4(a). There are two different kinds of waves that may cause energy leakage. One is the parallel plate wave supported by the infinitely extended parallel plates with dielectric layer ε_{r3} inside, which is the cause for the leakage in single-layered conductor-backed coplanar waveguide. The relevant dominant parallel plate mode is TEM mode with effective dielectric constant equal to ε_{r3}. The other is surface wave supported by a grounded dielectric layer ε_{r2} and a top metal cover, which causes the leakage in the conventional coplanar waveguide at high frequencies [14]. The relevant dominant surface wave mode in this case is LSM_0 and its propagation constant can be obtained by solving the following equation [15]:

$$\frac{p}{\varepsilon_{r1}} \tanh(ph_1) = \frac{q}{\varepsilon_{r2}} \tan(qh_2) \tag{2a}$$

$$\beta^2 - p^2 = \varepsilon_{r1} k_0^2 \tag{2b}$$

$$\beta^2 + q^2 = \varepsilon_{r2} k_0^2. \tag{2c}$$

Fig. 5 presents the variations of normalized phase constant β/k_0 (square root of effective dielectric constant) and normalized attenuation constant α/k_0 as a function of top layer thickness h_2 at a given frequency (50 GHz). For small thickness h_2, the dominant CPW mode is faster than the dominant parallel plate wave because its normalized phase constant is smaller than that of relevant dominant parallel plate mode. The dominant CPW mode is therefore leaky and the energy leaks away from the dominant CPW mode in the form of parallel plate wave. There is no energy leakage in the form of surface wave because the dominant CPW mode is slower than the relevant surface wave mode. As h_2 is increased, the normalized phase constant of the dominant CPW mode increases and the attenuation constant decreases. The attenuation constant suddenly drop to zero at the point $h_2 = 0.029$ mm where the normalized phase constant reaches the square root of relative dielectric constant ε_{r3} ($\sqrt{\varepsilon_{r3}} = \sqrt{2.33} = 1.526$), indicating that the leakage caused by the parallel plate wave ceases to exist. As the thickness h_2 is increased further, the normalized phase constants for both the dominant CPW mode and the relevant surface wave mode LSM_0 increase. However, the phase constant of LSM_0 increases faster and finally becomes larger than that of the dominant CPW mode. The dominant CPW mode is no longer purely bound and becomes leaky again. The energy leaks into transverse direction in the form of surface wave instead of parallel plate wave. There is a sharp minimum in attenuation constant at about $h_2 = 0.83$ mm.

The frequency dependence of the normalized phase and attenuation constants for this structure is shown in Fig. 6. With properly chosen ε_{r2} and h_2, the leakage caused by parallel plate wave is suppressed. At low frequencies, attenuation constant is zero where the normalized phase constant for the dominant CPW mode is higher than that of the relevant surface wave mode LSM_0. As frequency increases, both normalized phase constants of the dominant CPW and LSM_0 increase. However, LSM $_0$ is strongly dispersive and its normalized phase constant increases much faster than that of the dominant CPW mode as the frequency increases. At a certain frequency (onset of high frequency leakage) the dispersion curves for

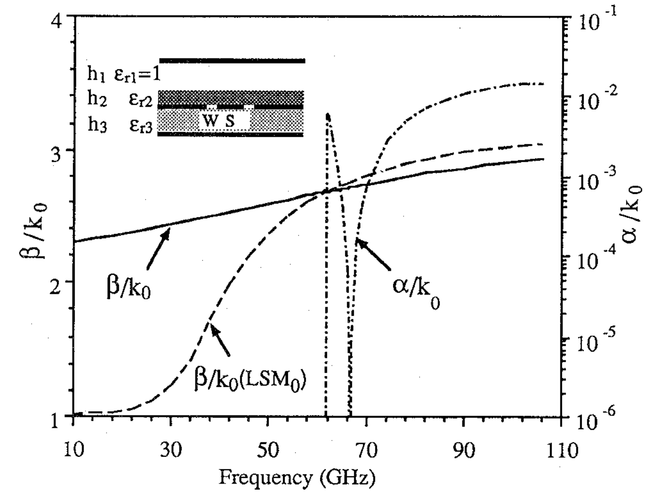

Fig. 6. Normalized phase and attenuation constants versus frequency. $\varepsilon_{r2} = 10.5$, $\varepsilon_{r3} = 2.33$, $W = 0.454$ mm, $S = 0.420$ mm, $h_1 = 20.0$ mm, $h_2 = 0.635$ mm, $h_3 = 0.381$ mm.

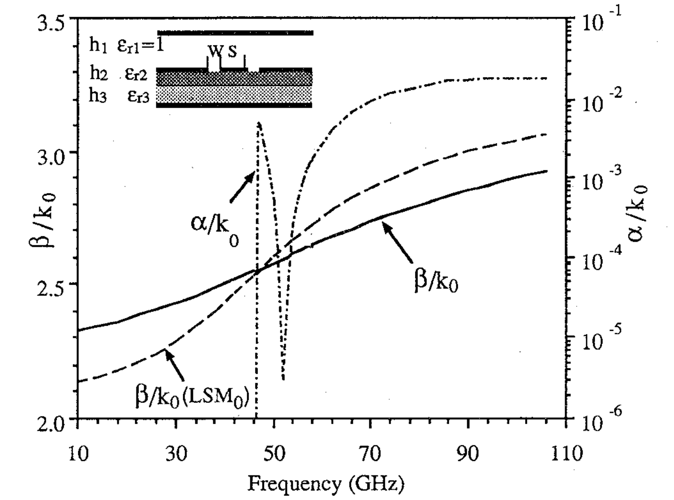

Fig. 8. Normalized phase and attenuationconstants versus frequency.$\varepsilon_{r2} = 10.5$, $\varepsilon_{r3} = 2.33$, $W = 0.454$ mm, $S = 0.420$ mm, $h_1 = 20.0$ mm, $h_=2$ 0.635 mm, $h_3 = 0.381$ mm.

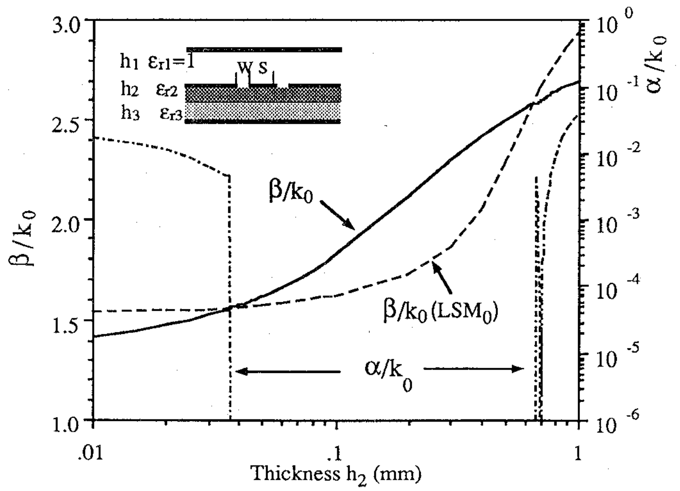

Fig. 7. Normalized phase and attenuation constants versus $h_2.\varepsilon_{r2} = 10.5$, $\varepsilon_{r3} = 2.33$, $W = 0.454$ mm, $S = 0.420$ mm, $h_1 = 20.0$ mm, $h_3 = 0.635$ mm, $f = 50$GHz.

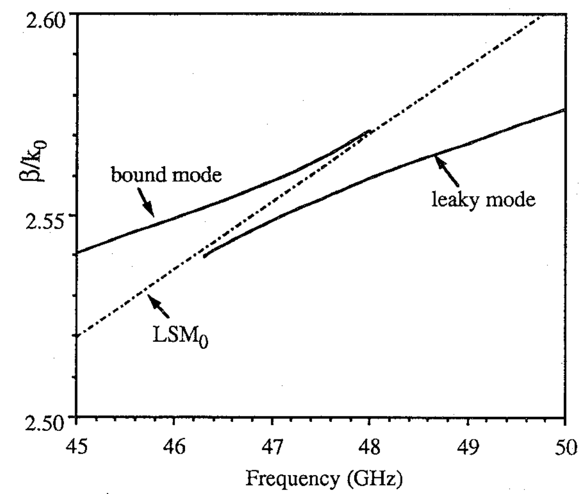

Fig. 9. Enlarged plot of transition region in Fig. 8.

the dominant CPW mode and LSM_0 cross each other. Above this frequency, the dominant CPW mode is no longer purely bound and becomes leaky. The energy leaks away from the dominant CPW mode in the form of surface wave. A sharp minimum in attenuation constant occurs at frequency 67 GHz. Such high frequency leakage phenomenon is similar to the one in conventional coplanar waveguide as described in [14], [16].

The structure shown in Fig. 4(b) shows similar behaviors. However, there is only one type of wave (supported by infinitely extended parallel plates with two dielectric layers inside) that causes the energy leakage. The relevant dominant parallel plate mode is LSM_0. As shown in Fig. 7, the dominant CPW mode is leaky for both small h_2 ($h_2 < 0.037$ mm) and large h_2 ($h_2 > 0.65$ mm) where the normalized phase constant of the dominant CPW mode is lower than that of LSM_0. The normalized phase constant of the dominant CPW mode is larger than that of LSM_0 for moderate h_2 (0.037 mm $< h_2 <$ 0.65 mm) and the dominant CPW mode is purely bound in this region. Fig. 8 shows the frequency dependence of normalized phase and attenuation constants. The dominant CPW mode is purely bound at low frequencies and becomes leaky at high frequencies (onset frequency is about 46 GHz). Again, similar sharp minima in attenuation constant are observed.

One common feature of Figs. (5)–(8) is that there exists a mode transition from bound to leaky or vise versa. Detailed investigation reveals that these transitions show similar behavior. The transition region in Fig. 8 is shown in Fig. 9 in an extended scale as an example. It should be noticed that both bound (non-leaky) and leaky modes exist simultaneously in this transition region. Another common feature is the sharp minimum in the attenuation constant. All these features are similar to the ones in the conventional single layered coplanar waveguide where leakage occurs at high frequency due to surface wave. They have been investigated extensively by M. Tsuji, H. Shigesawa, and A. A. Oliner and reported in their publications [14], [16]–[18].

In conclusion to our theoretical discussion, the dominant CPW modes of the multilayered structures shown in Fig. 4(a) and (b) are purely bound over certain frequency range if

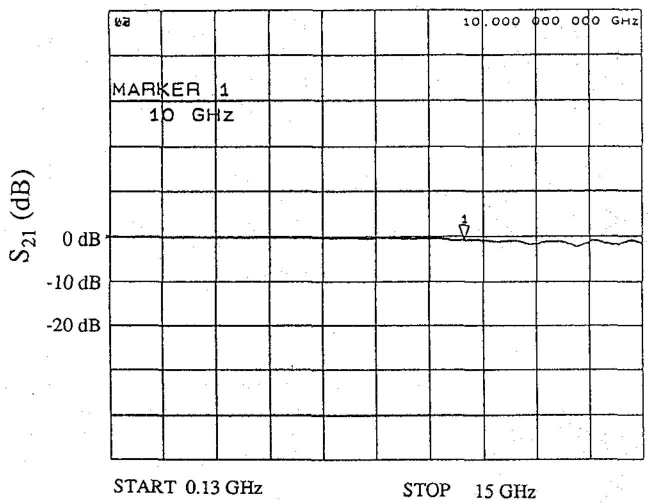

Fig. 10. S_{21} for conventional CPW.

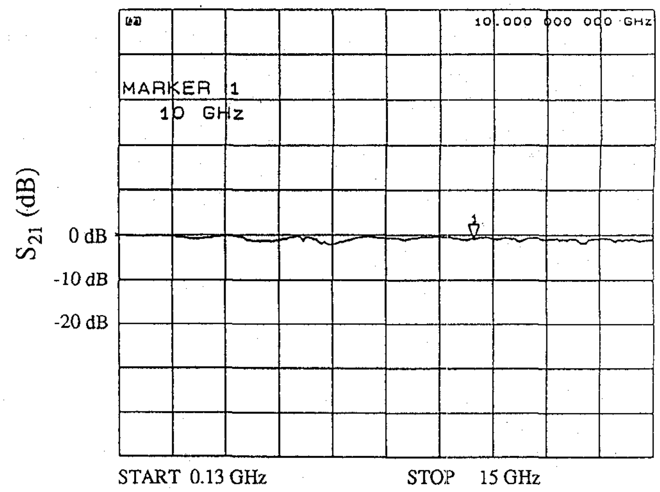

Fig. 12. S_{21} for FW-NLC waveguide shown in Fig. 4(a).

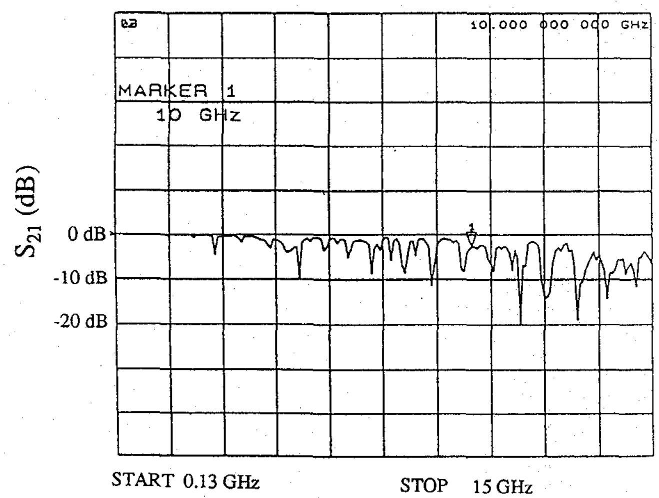

Fig. 11. S_{21} for FW-CBCPW shown in Fig.

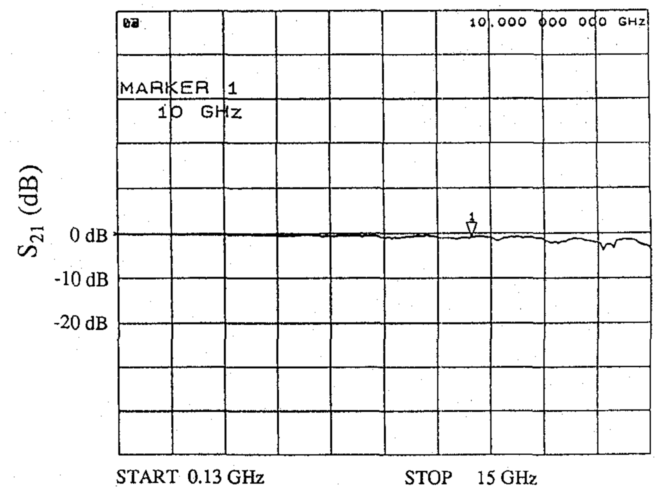

Fig. 13. S_{21} for FW-NLC waveguide shown in Fig. 4(b).

the geometrical and material parameters of the structure are chosen properly. However, the dominant CPW mode of the multilayered structure becomes leaky at high frequencies. This high-frequency leakage is similar to the one in the conventional single layered coplanar waveguide. The onset frequency of leakage is determined by geometrical and material parameters of the structure. Careful design is therefore necessary in order to obtain a non-leaky coplanar (NLC) waveguide with conductor backing.

III. Experiments

The coplanar waveguides shown in Figs. 1 and 4 have been fabricated, with circuit dimensions of 44.5 × 38.1 mm. The relative dielectric constants ε_{r2} and ε_{r3} are 10.8 and 2.33, respectively. The thicknesses are 0.7874 and 0.635 mm for ε_{r2} layer and ε_{r3} layer, respectively. The center conductor width S and slot gap W are chosen so that the characteristic impedance of the line is 50 Ohms at 10 GHz. Two coplanar waveguides shown in Fig. 2 are non-leaky in the experiment frequency range (0–15 GHz) according to our theoretical calculation. The waveguide transmission characteristics are then measured by the network analyzer HP8720.

Figs. 10 and 11 show the transmission S_{21} for the conventional CPW and FW-CBCPW, respectively. Many resonances are observed with FW-CBCPW as reported in [8]. They are separated by equal frequency interval. The resonance is caused by the leaky wave in the form of parallel plate waves that bounce back and forth inside the circuit due to the circuit truncation. The results of S_{21} for two finite-width non-leaky coplanar (FW-NLC) waveguides are shown in Figs. 12 and 13, respectively. As we expected, the resonance is eliminated and transmission characteristic is improved because the resonance excitation source is eliminated in these structures. The results confirm our theoretical predication that the leakage is removed in these two NLC waveguides.

IV. Conclusion

A non-leaky coplanar (NLC) waveguide is proposed and two possible configurations are presented. Spectral domain approach with a complex root searching procedure is used to investigate the leaky wave propagation. The simulation results show that the dominant CPW mode in the NLC waveguide is purely bound over certain frequency range. Leakage in these structures occurs at high frequencies in a similar way as one in the conventional single layered coplanar waveguide. Experiments were carried out and the results show that the resonance occurring in the transmission of finite-width conductor-backed coplanar waveguide (FW-CBCPW) is removed in the NLC waveguides. These NLC waveguides are practical and feasible in the uniplanar MMIC circuit design because of their planar nature.

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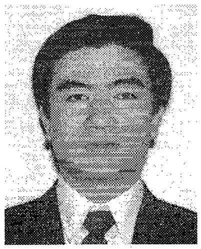

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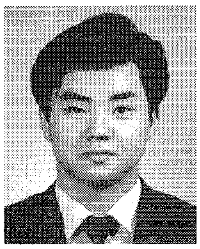

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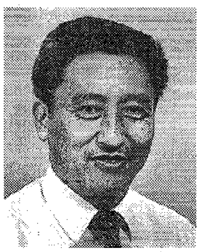

Tatsuo Itoh (S'69–M'69–SM'74–F'82) received the Ph.D. Degree in electrical engineering from the University of Illinois, Urbana, in 1969.

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